Kaon Electroproduction on the Nucleon

Cornelius Bennhold
George Washington University

- **Why?**
  - **to test strong QCD!**
- **How?**
  - **SU(3) Chiral Perturbation Theory**
    - ✓Threshold γ**N**$\rightarrow$KΛ amplitudes
    - ✓K^+, K^0, Λ form factors, polarizabilities
  - **Lattice QCD**
    - ✓Excitation spectrum of the nucleon
    - ✓"Missing" and exotic resonances

What do we want?

New Topic

Quantum Chromodynamics (QCD)

--- the fundamental theory of the strong interaction (in terms of quarks and gluons)

$$L_{QCD} = \frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \bar{q}(\gamma^{\mu}D_{\mu} + m_q)q$$

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Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. For N, Δ, and Ξ resonances, the partial wave is indicated by the symbol $L_{2I,2J}$, where L is the orbital angular momuntum (S, P, D, ...), I is the isospin, and J is the total angular momentum. For Λ and Σ resonances, the symbol is $L_{I,2J}$.

p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**

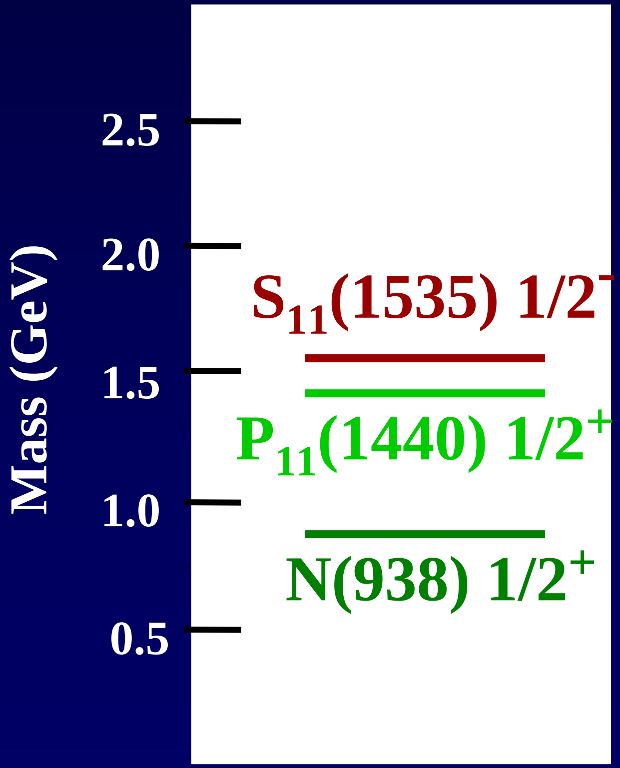
Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	**
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	**
$\Sigma(2100)$	G_{17}	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

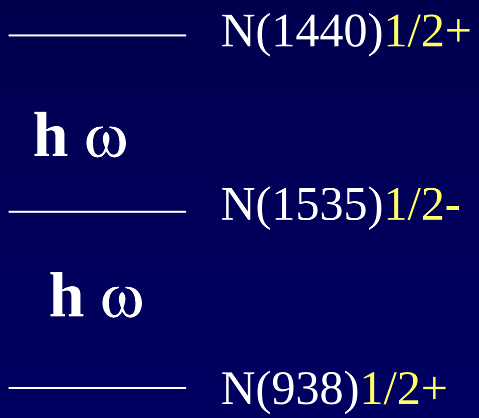
Ξ^0, Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+		****
$\Lambda_c(2593)^+$		***
$\Lambda_c(2625)^+$		***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$		**
$\Sigma_c(2455)$		****
$\Sigma_c(2520)$		***
Ξ_c^+, Ξ_c^0		***
$\Xi_c'^+$, $\Xi_c'^0$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Λ_b^0		***
Ξ_b^0, Ξ_b^-		*

Comparison with lattice results

What is the nature of the Roper (P_{11}(1440) $1/2^+$) resonance?

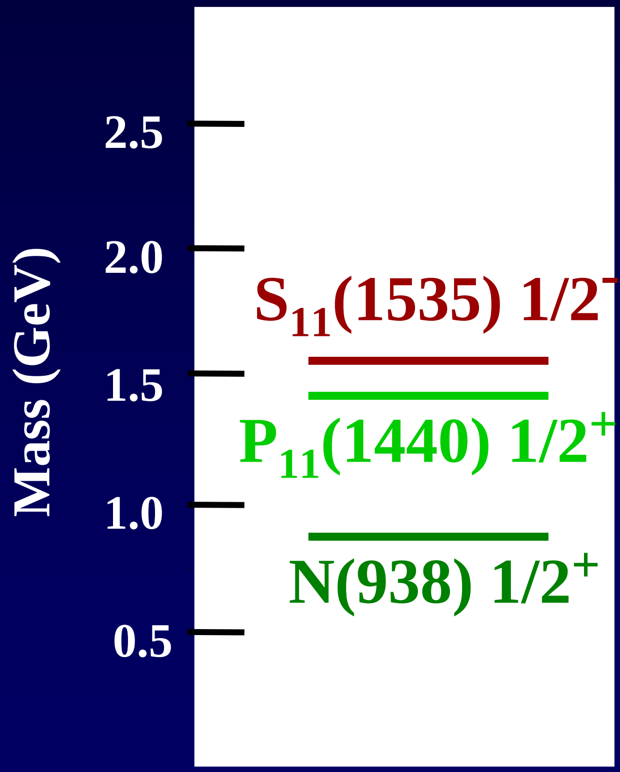


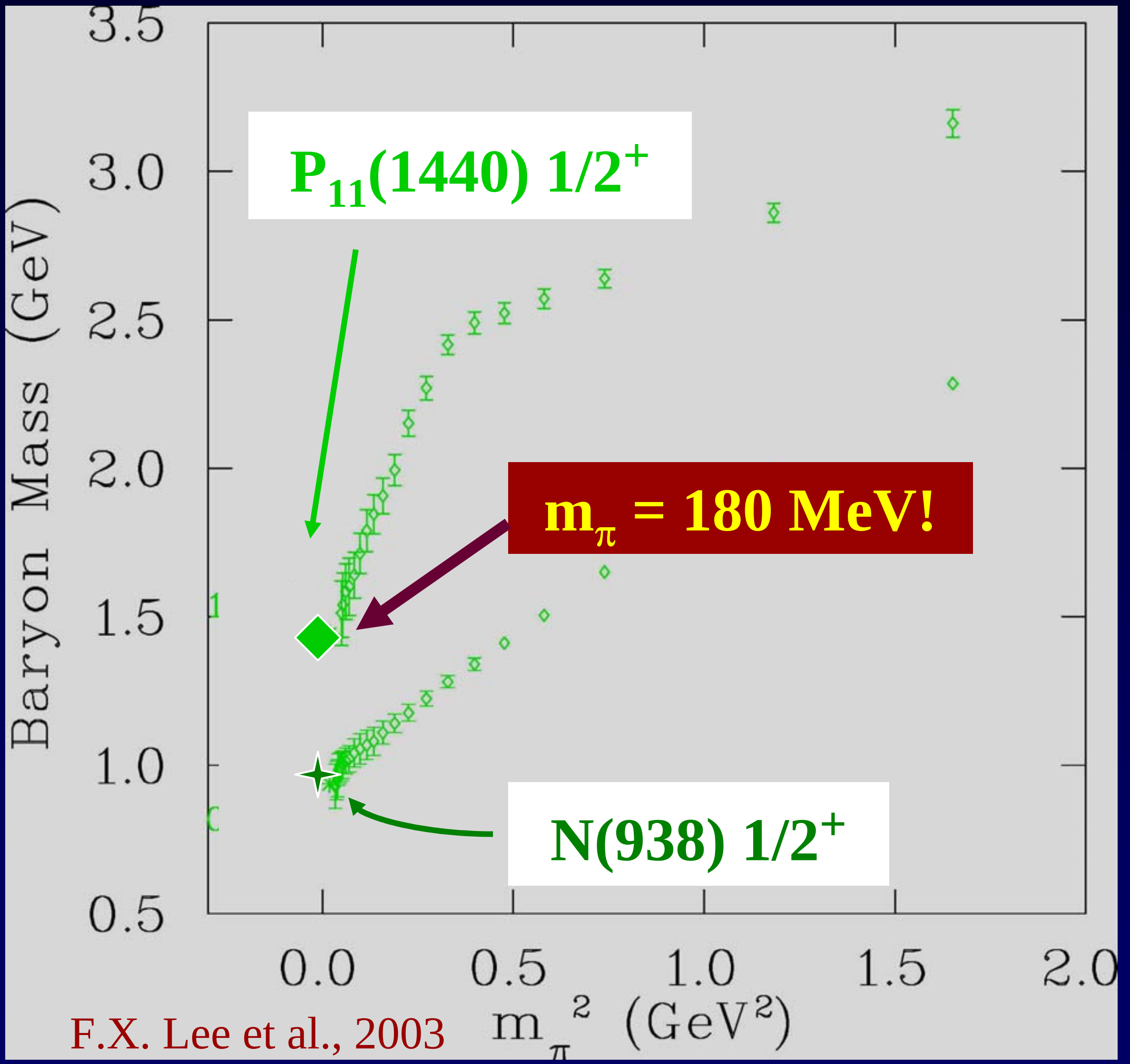
Naïve quark model gives the wrong ordering



- Hybrid state (qqq*g*)?
- Dynamical meson-baryon state?

What is the nature of the Roper (P_{11}(1440) $1/2^+$) resonance?

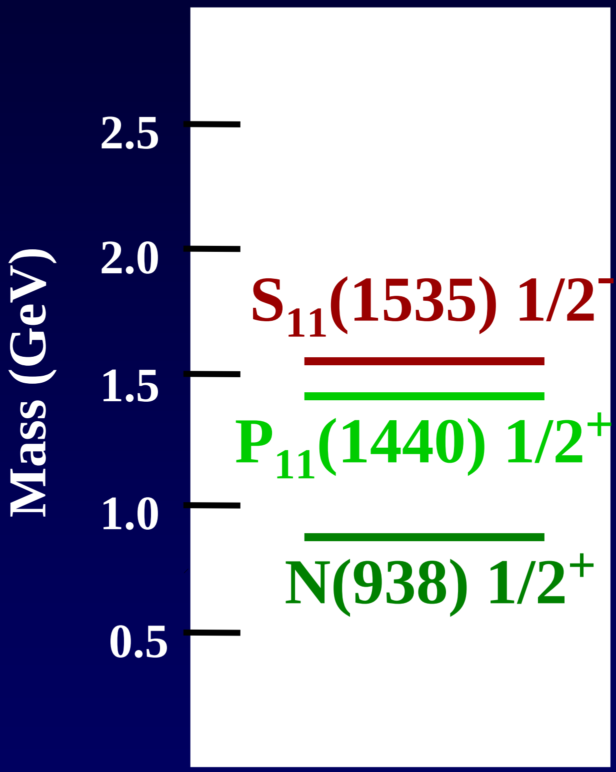


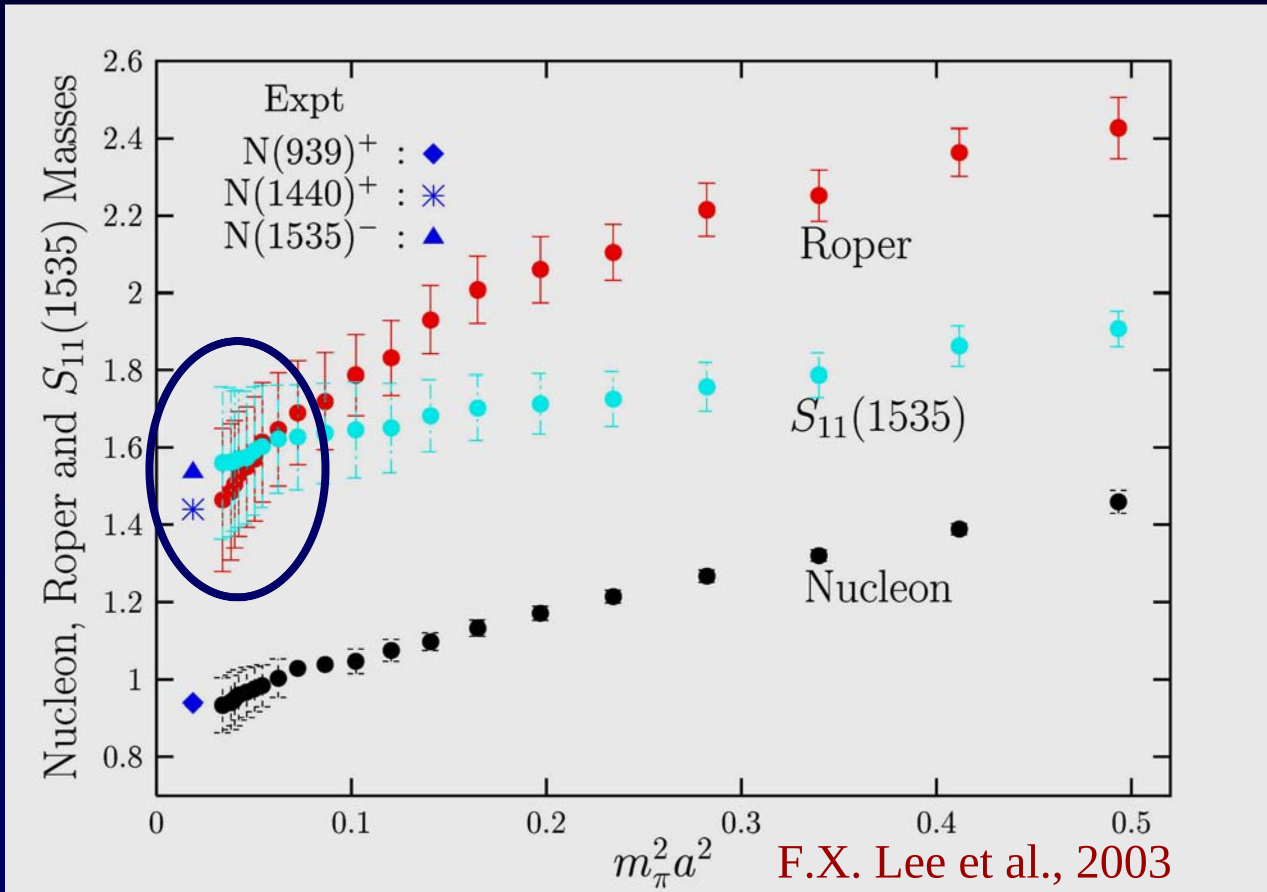


F.X. Lee et al., 2003

Answer: The Roper (P_{11}(1440) $1/2^+$) is just a regular 3-quark state!

Can we understand the level ordering?

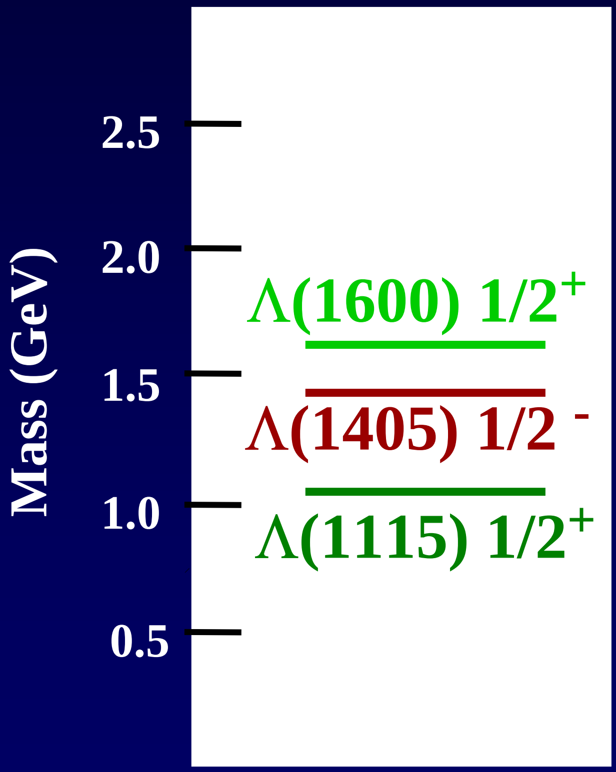


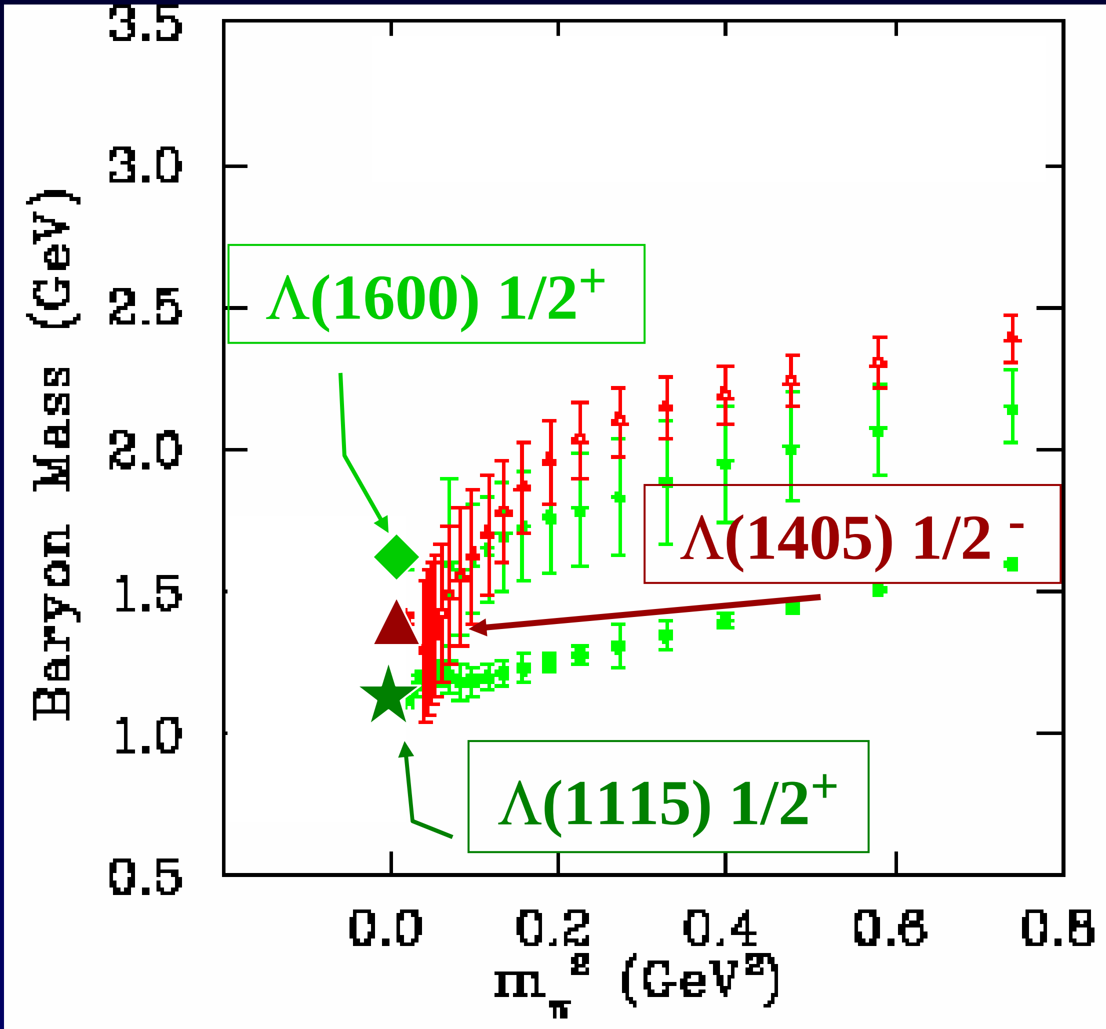


F.X. Lee et al., 2003

Cross over occurs very close to chiral limit!

What about Hyperons? The Λ(1405)?



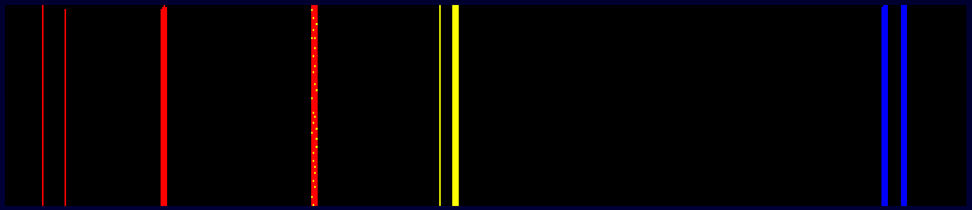


Talk by Frank Lee on Friday…

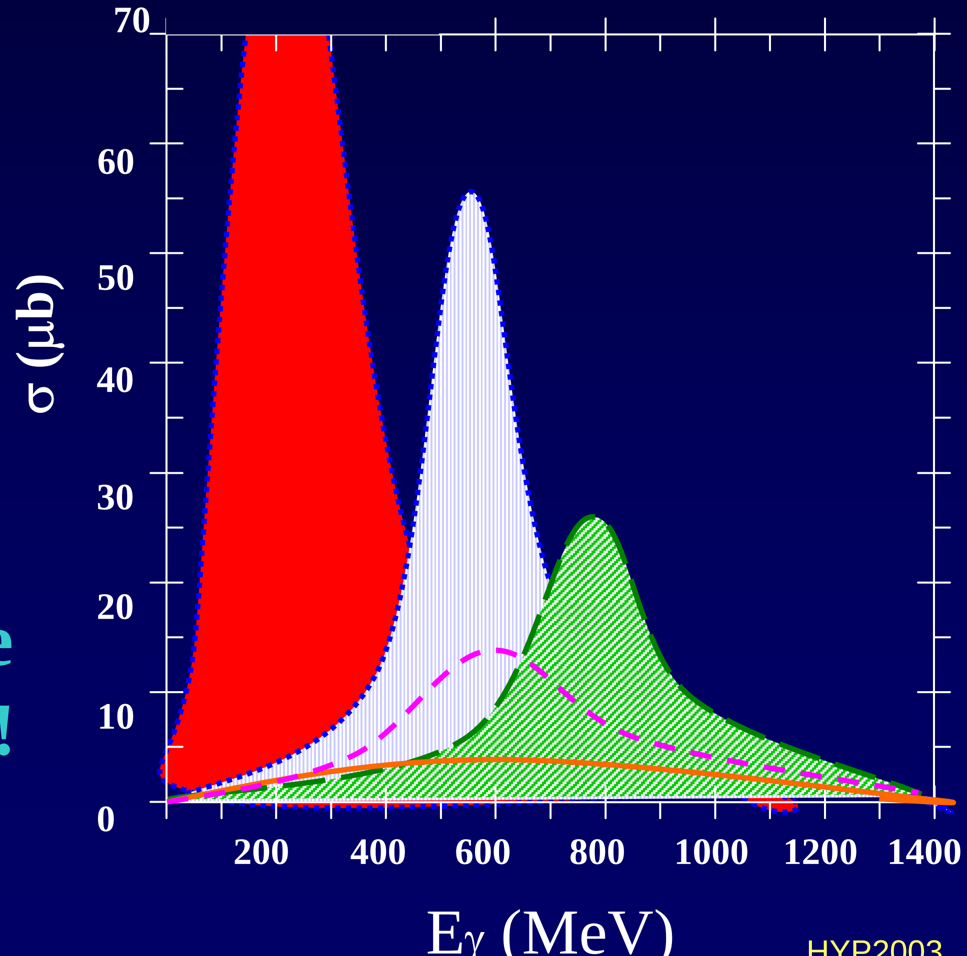
How do we find the resonances?

New Topic

N* spectral "lines" don't quite look like this:

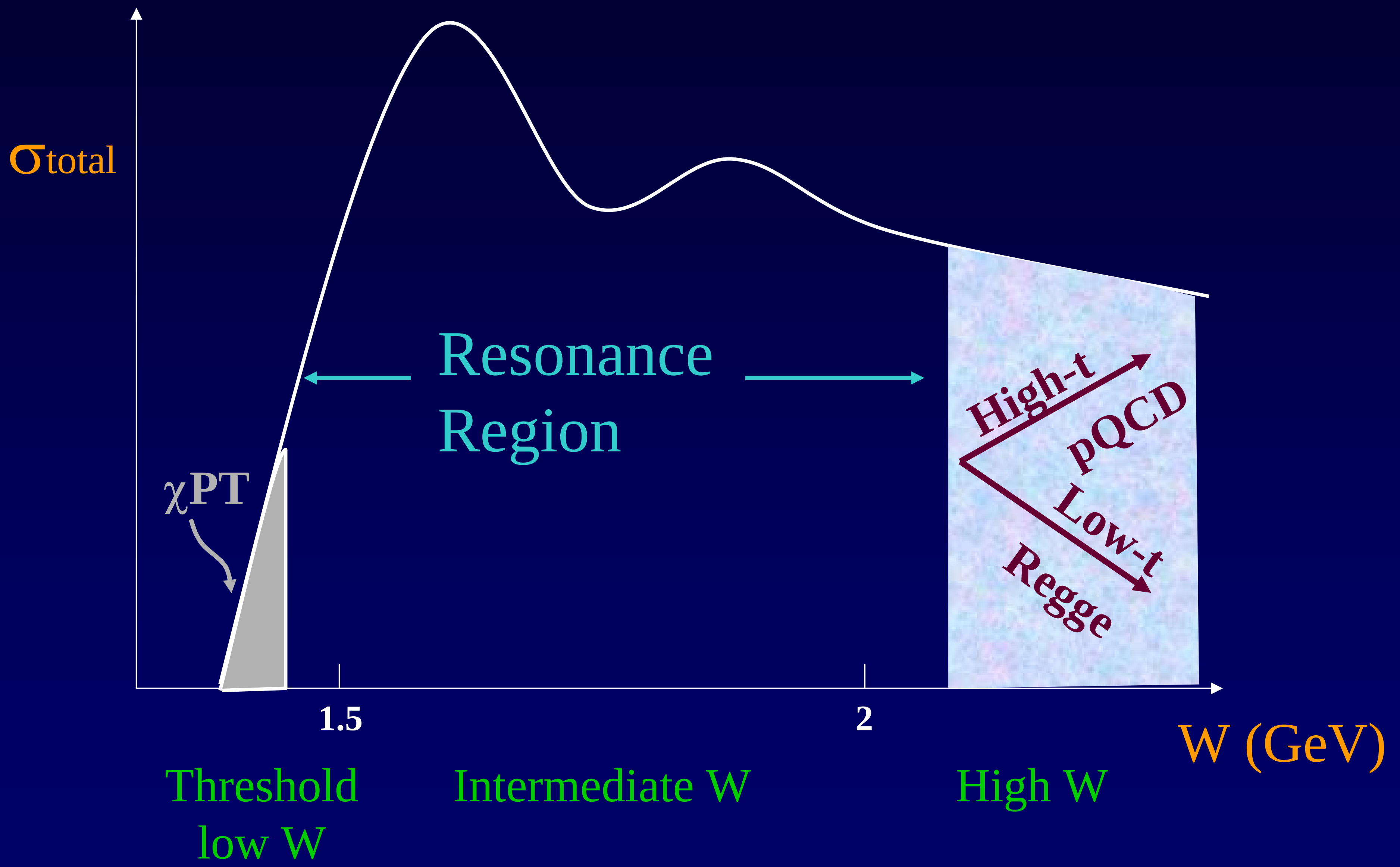


…but more like this:



Nucleon resonances are broad and overlapping!

$\gamma N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, \ldots$



We cannot directly compare experiment to QCD…

…therefore, we must use an "intermediary":

QCD Lattice, Quark models

M_{N^*}, $\Gamma_{\pi N}$, $A_{1/2}$ →

Dynamical Models:
mesons + Baryons

← ***Multipoles***
Phase shifts

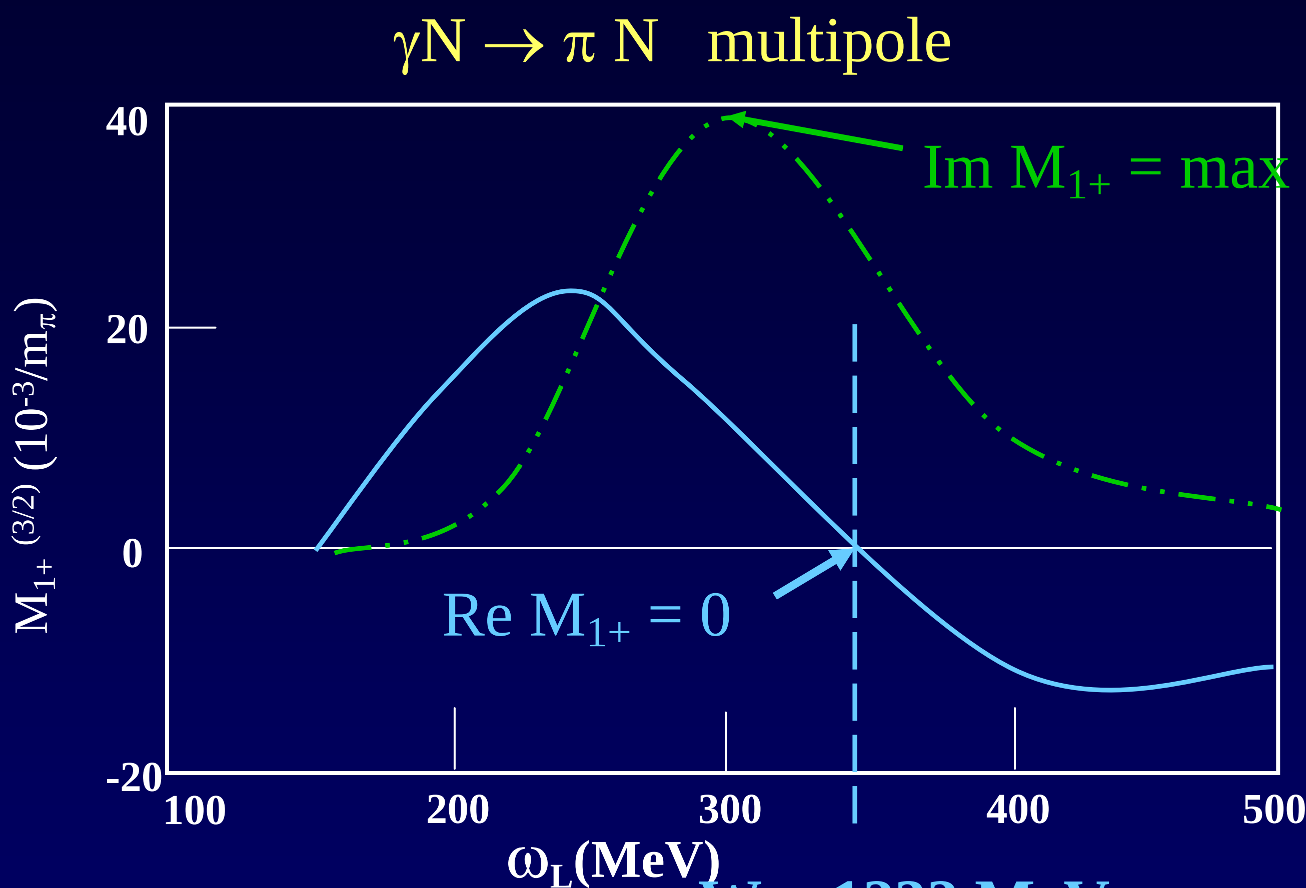
Experiments:
$\gamma N \to \pi N, \pi\pi N$
$\eta N, K\Lambda, \ldots$
$\pi N \to \pi N, \pi\pi N$
$\eta N, K\Lambda, \ldots$

Theoretical challenge: Resolution of broad, overlapping resonances in a strongly-coupled, multi-channel system

A theorist's approach to finding N*s…

- Step 1: Measure *all* observables for *all* channels at *all* energies and *all* angles!
- Step 2: Perform *partial wave analysis*
- Step 3: Fit model parameters to extracted partial waves
- Step 4: Separate background from resonance contributions
- Step 5: Extract resonance properties and compare to lattice

How does a partial-wave amplitude behave at $E = E_{res}$?



W = 1232 MeV

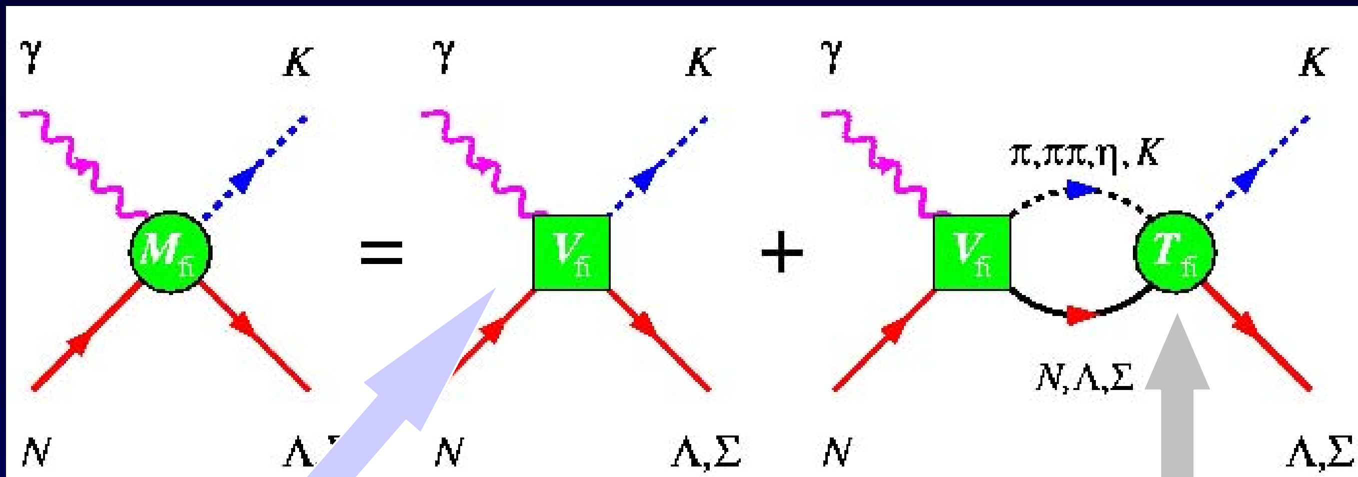
$$T_l(E) \sim \frac{\Gamma/2}{(E-E_R) - i\Gamma/2}$$

$$\sim \frac{\Gamma/2}{(E-E_R)^2 + (\Gamma/2)^2} \left((E-E_R) + i\Gamma/2\right)$$

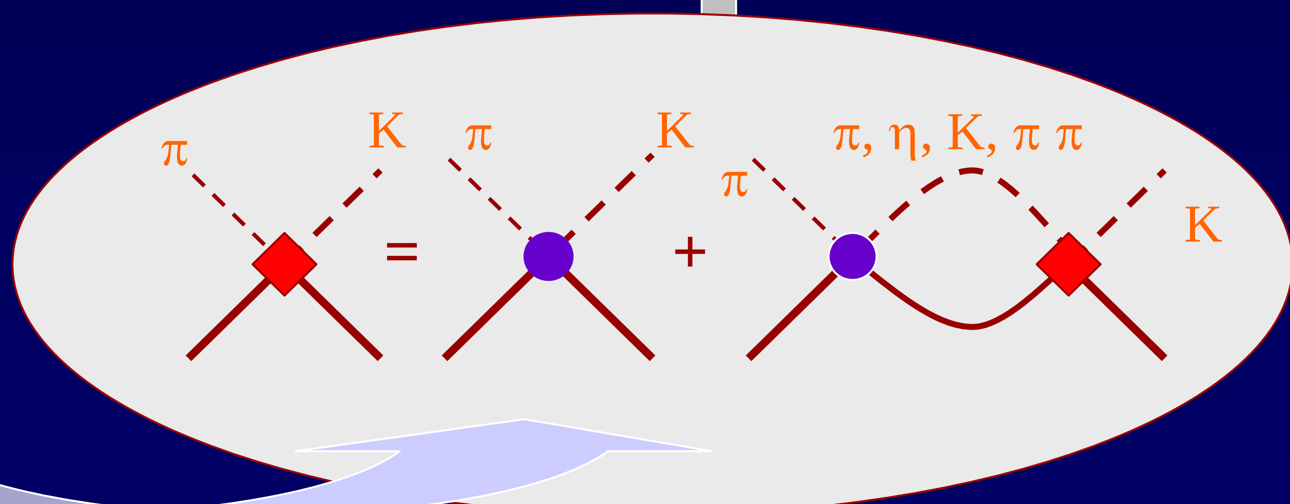
where $(E-E_R)$ gives **ReT_l** and $i\Gamma/2$ gives **ImT_l**.

<u>Caution:</u> Single resonance, elastic, no background!

Scattering amplitude: $M = V + \int V\, G_0\, T$

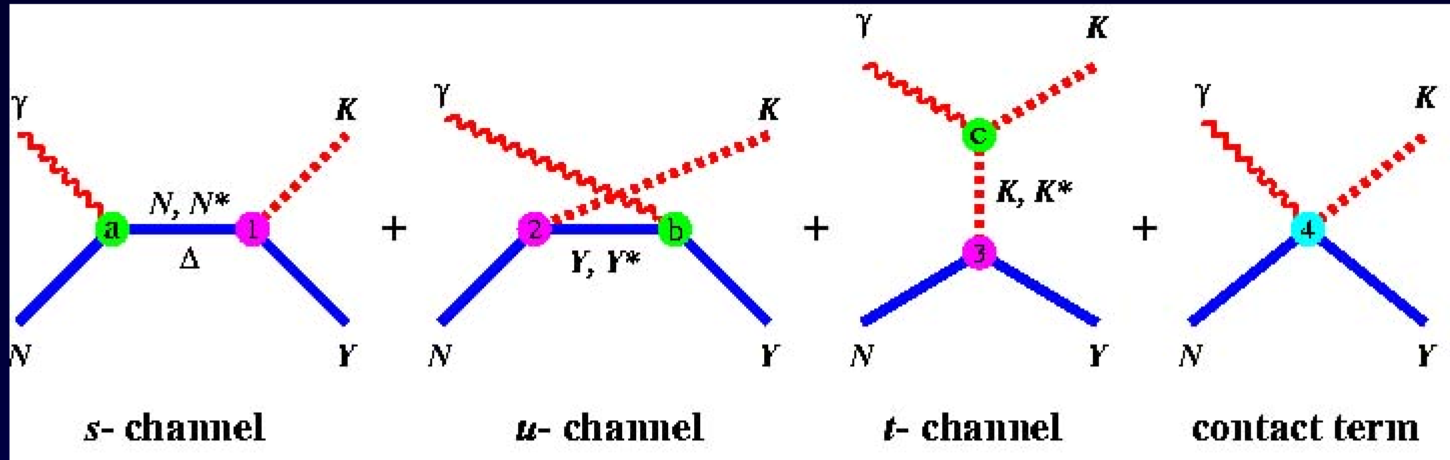


Hadronic rescattering amplitude:



The physics is in the driving terms

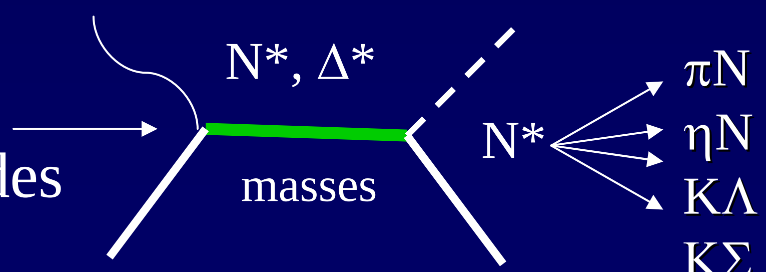
Driving (potential) terms



- SU(3) chiral dynamics:
  - Derivative couplings
  - Contact terms to a given order
- At high energies: t-channel contributions → Regge behavior

Resonance contributions

$A_{1/2}$, $A_{3/2}$
helicity amplitudes



branching ratios

Free parameters adjusted to data

How many N* do we have?

State-of-the-art multi-channel analyses find, *for a given partial wave:*

- Ground states (1st tier): P_{33}(1232), D_{13}(1520),…
  - Clear resonance signal, Mass known to within a few %.
  - $A_{1/2}$, Γ_{total}, partial widths fairly well known
  - Exceptions: S_{31}(1620),…
- 2nd tier states: P_{33}(1600), D_{13}(1700), …
  - Existence confirmed, but poorly understood
- 3rd tier states: P_{33}(1920), D_{13}(2080), …
  - Existence controversial. *Where is everybody?*

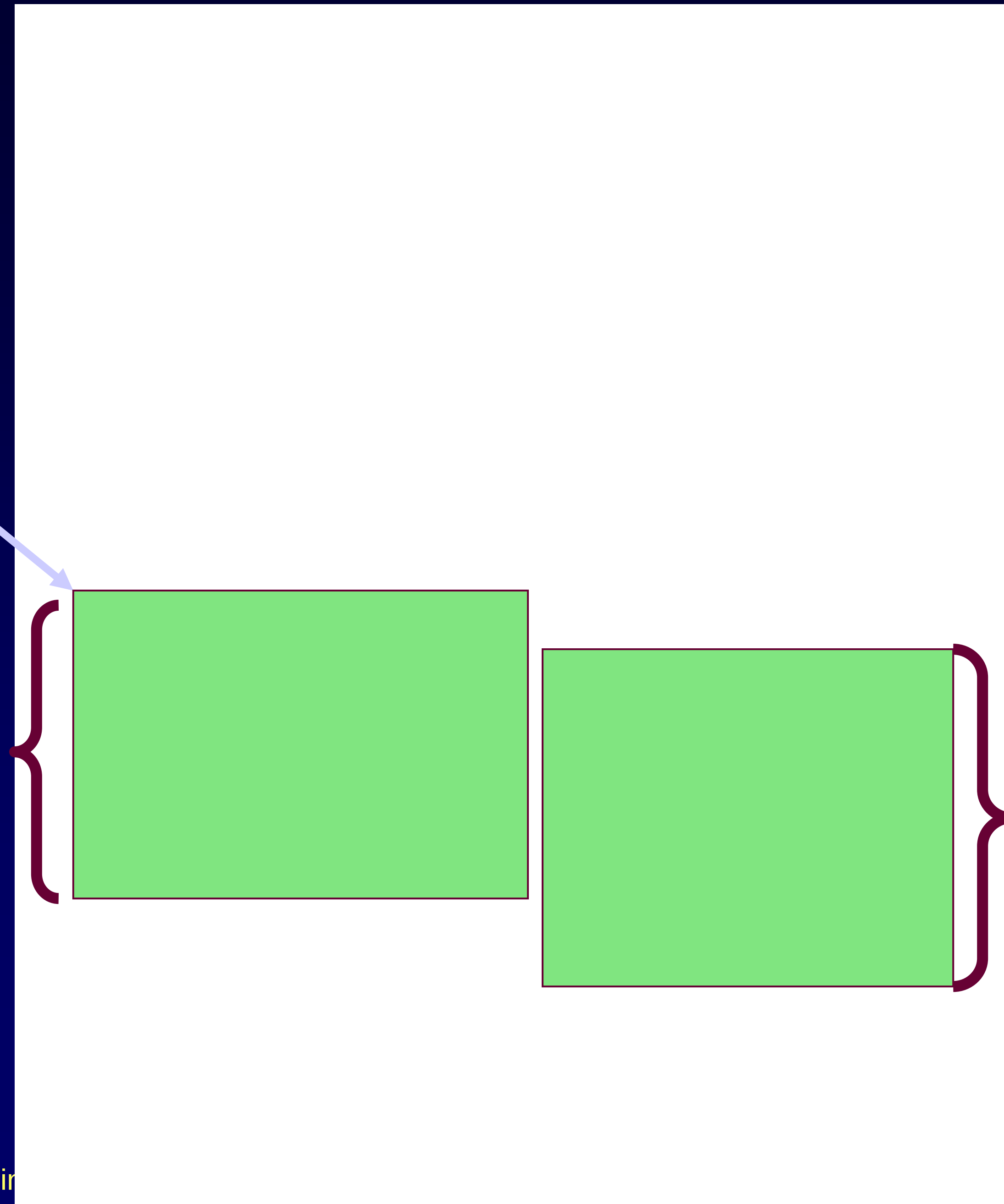
How many N* do we need?

What are “missing” Resonances?

New Topic

Current spectrum of *baryon resonances*:

Gap of almost 200 MeV with *no* N*



Gap of ≈450 MeV between 4-star N*

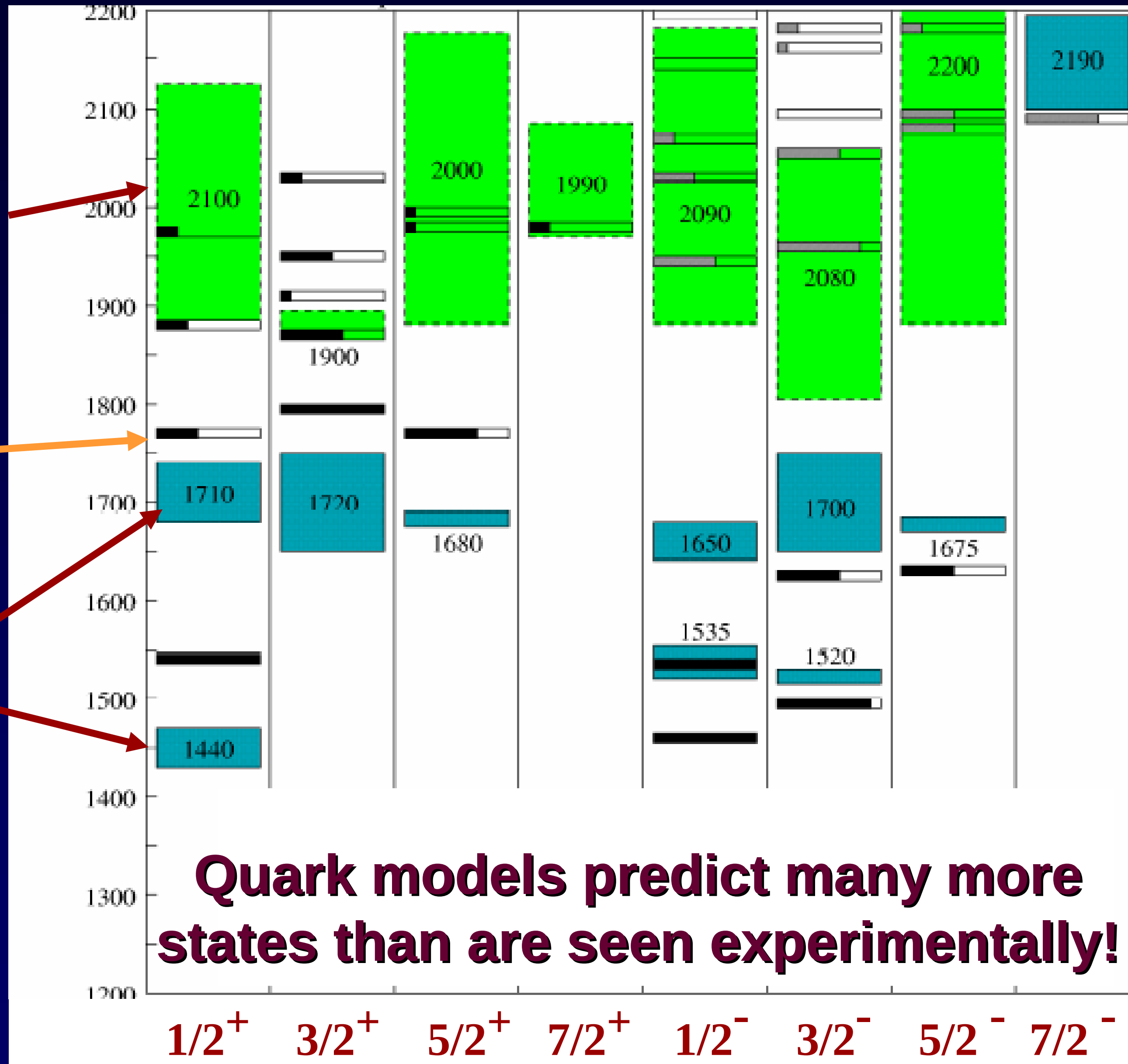
Gap of ≈450 MeV between 4-star Δ*

Compare experimental N* and quark model states

experimentally uncertain N*

Quark model predictions

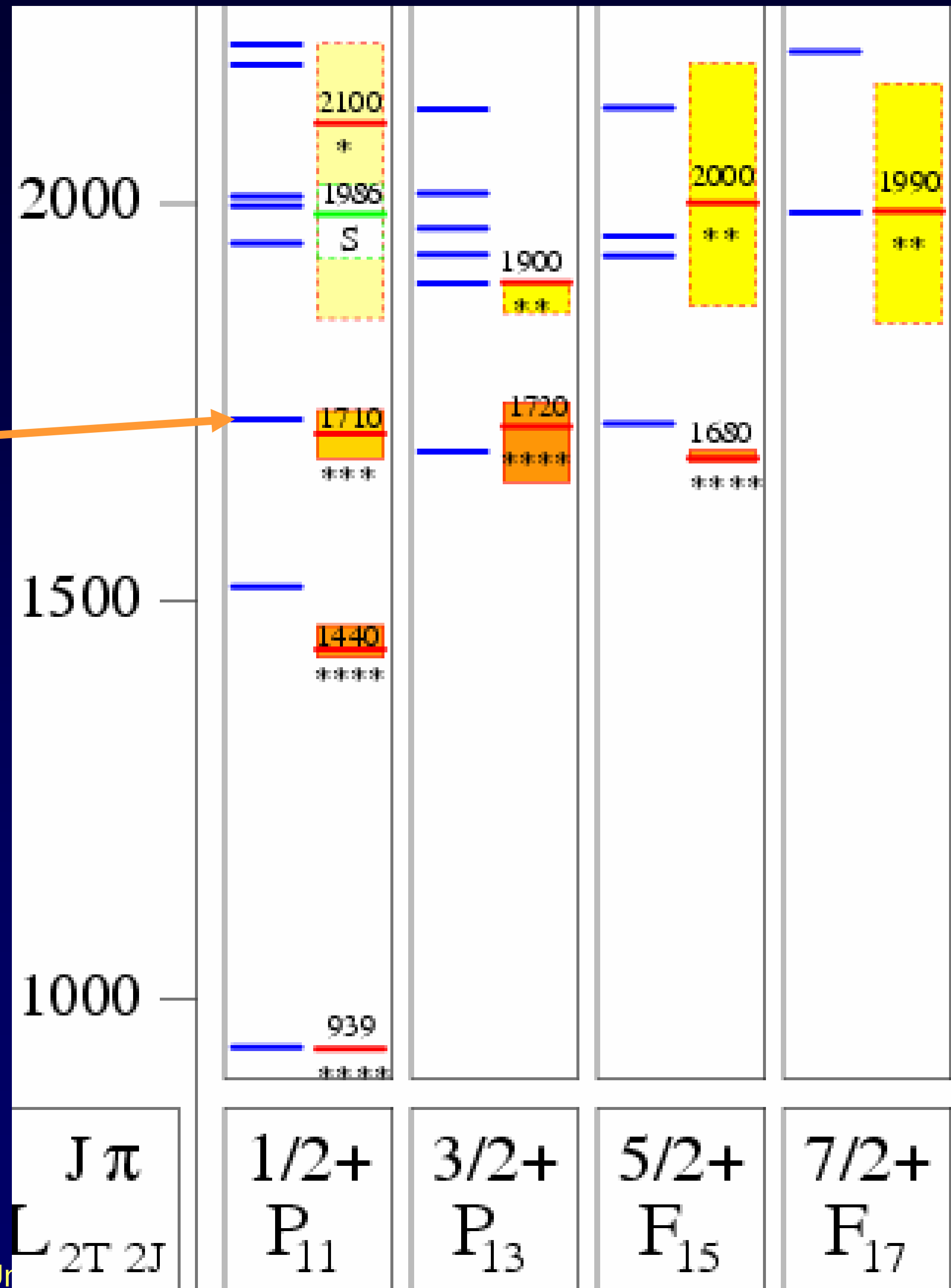
experimentally known N*



Capstick and Roberts quark model

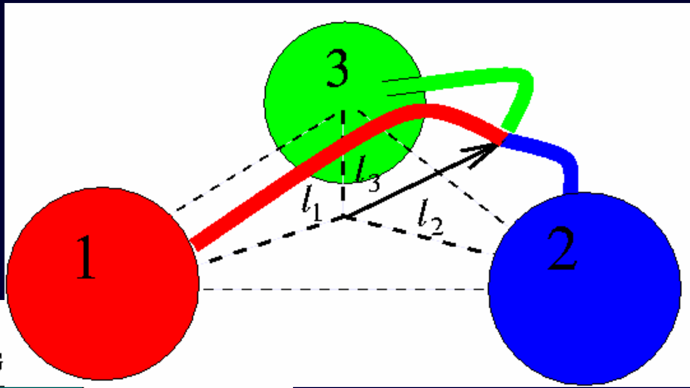
True for all models based on three constituent quarks

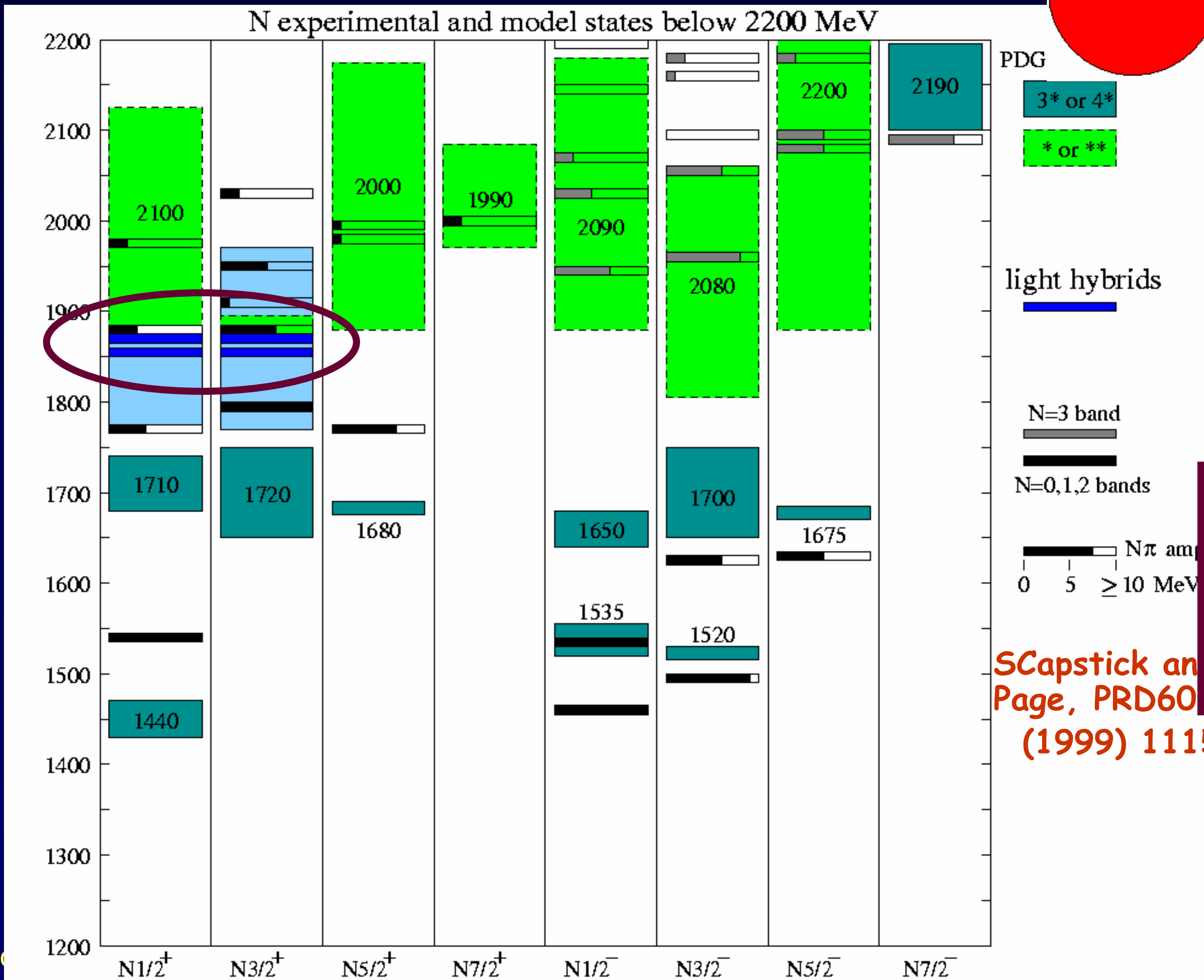
Quark model predictions



Metsch and Petry quark model

Nucleon flux-tube hybrids:





SCapstick an
Page, PRD60
(1999) 111501

Even more missing states!!!

Let's focus on the P_{13} ($3/2^+$) states:

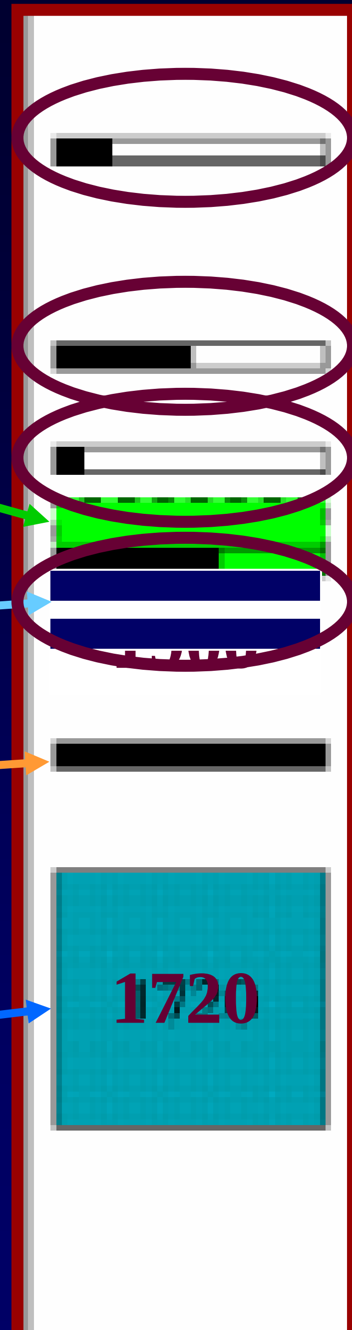
Five extra states below W = 2100 MeV!

experimentally uncertain N*

Light hybrids

Quark model predictions

experimentally known N*



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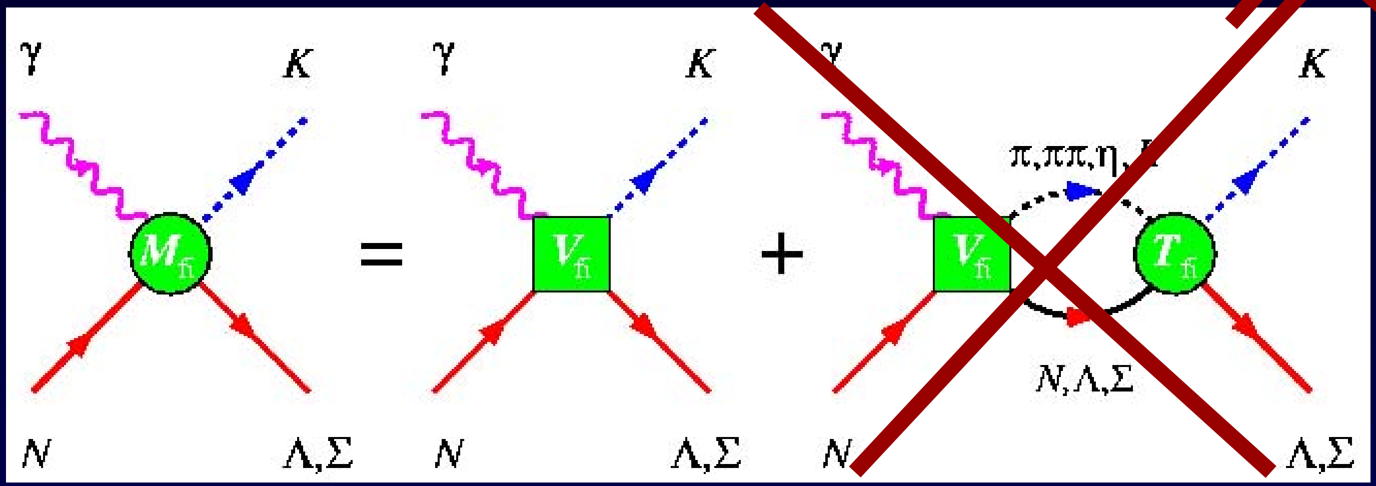
How many N* do we need?

Possibly 4-5 N* for selected partial waves!

…looking in **Strange** places: $\gamma N \rightarrow K\Lambda(\Sigma)$

New Topic

Scattering amplitude: $M = V + \int V\, G_0\, T$

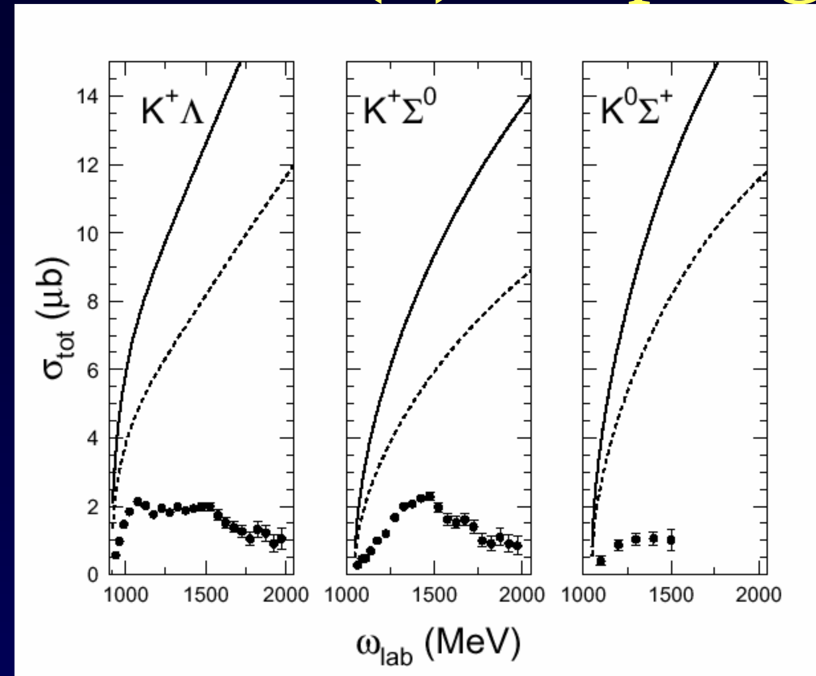


From coupled channels to single channel:

T=

$\mathbf{T}_{\gamma N \to K\Lambda}$

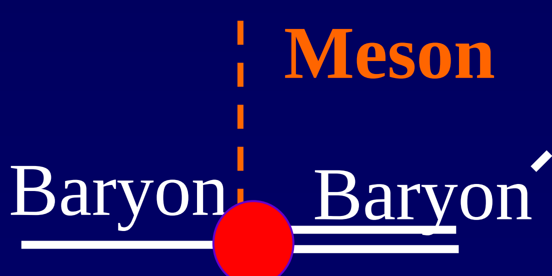
Background: tree level with SU(3) couplings

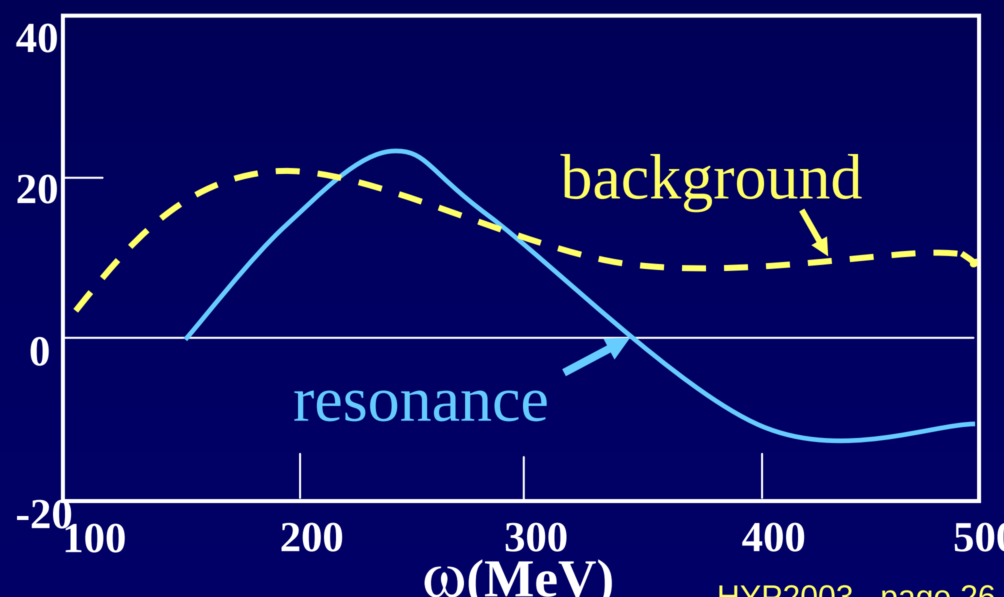


Diseaster!

Hadronic form factors:

Vertex × F(s,t,u)





γN→KΛ fits

Database:

- diff. cross section from SAPHIR or Jlab (not both!)
- Recoil polarization from SAPHIR or Jlab
- Photon asymmetry (SPring 8)

≈ 1300 data points

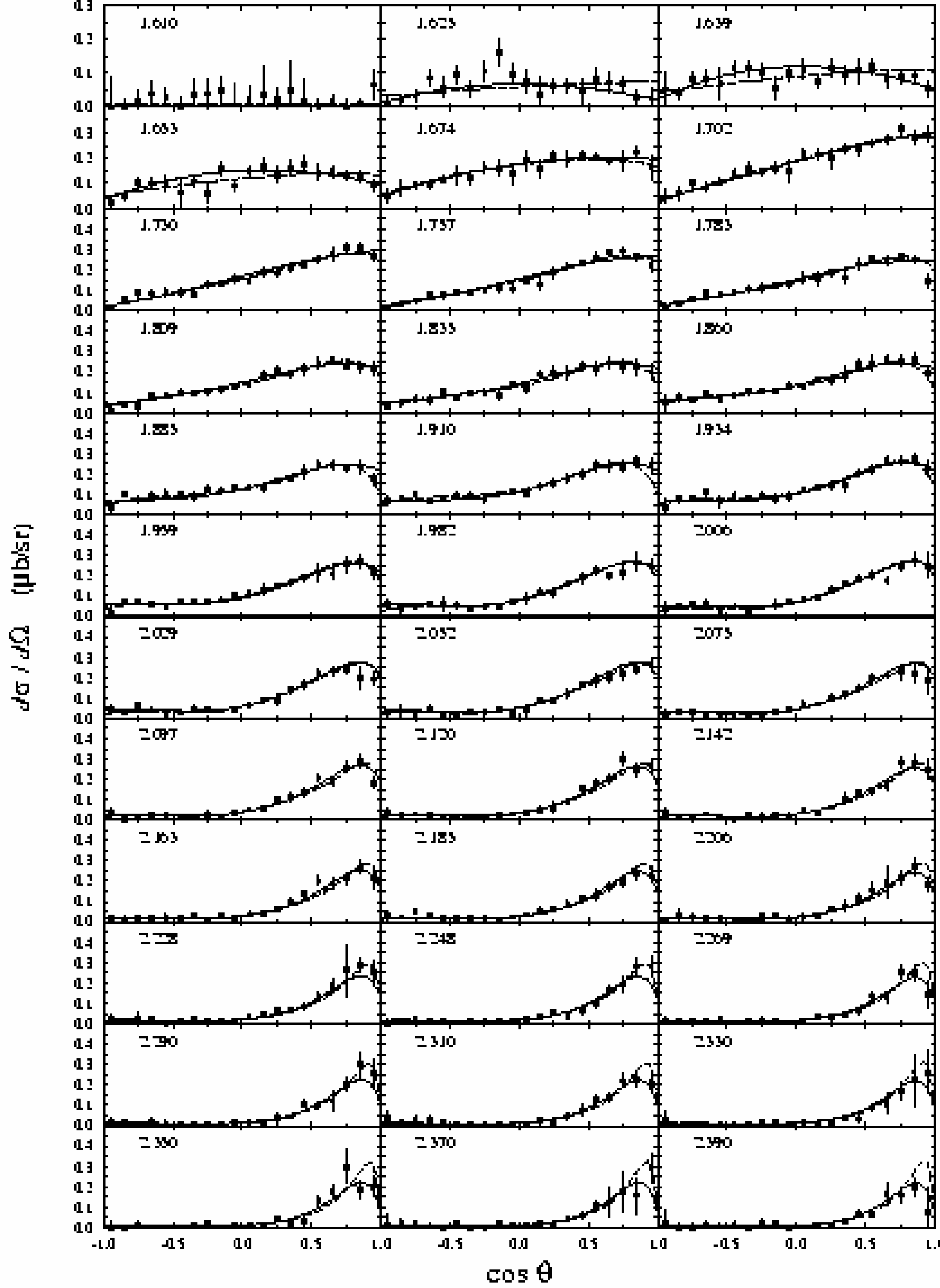
Model:

⇒ Born terms with form factors + 2 Y* in u-channel + K* in t-channel

⇒ ***6-8 N* states***

≈ 30-40 parameters

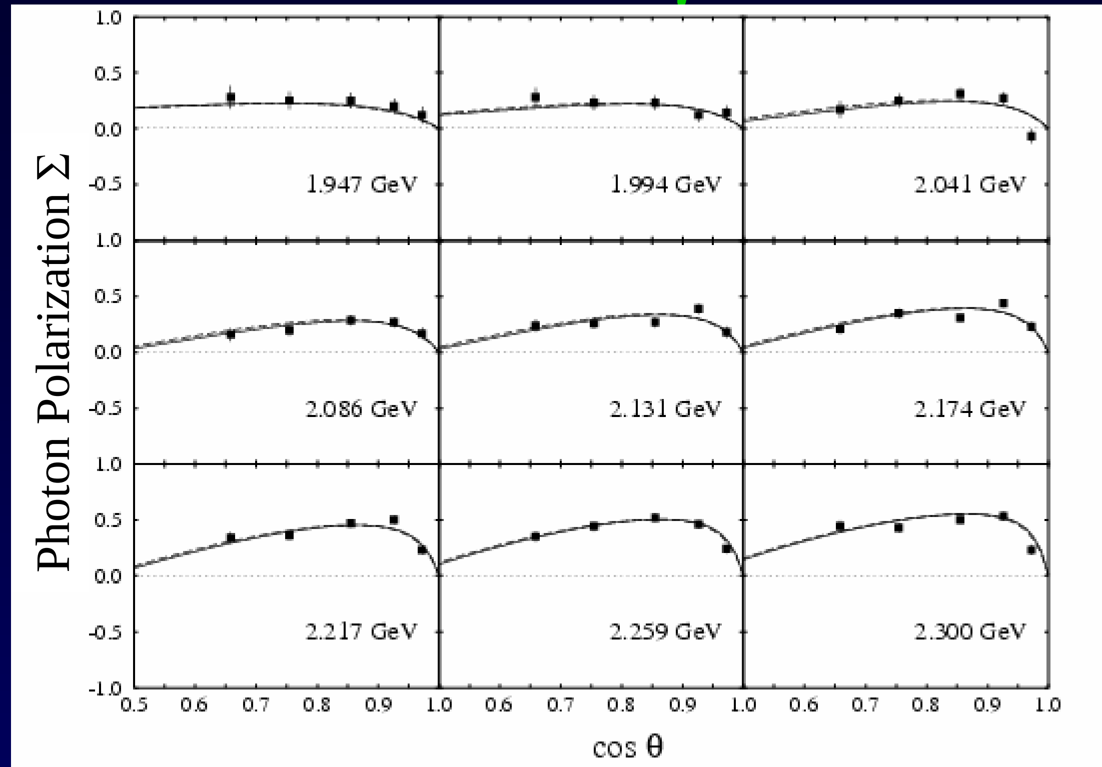
$\chi^2 \approx 1.1$



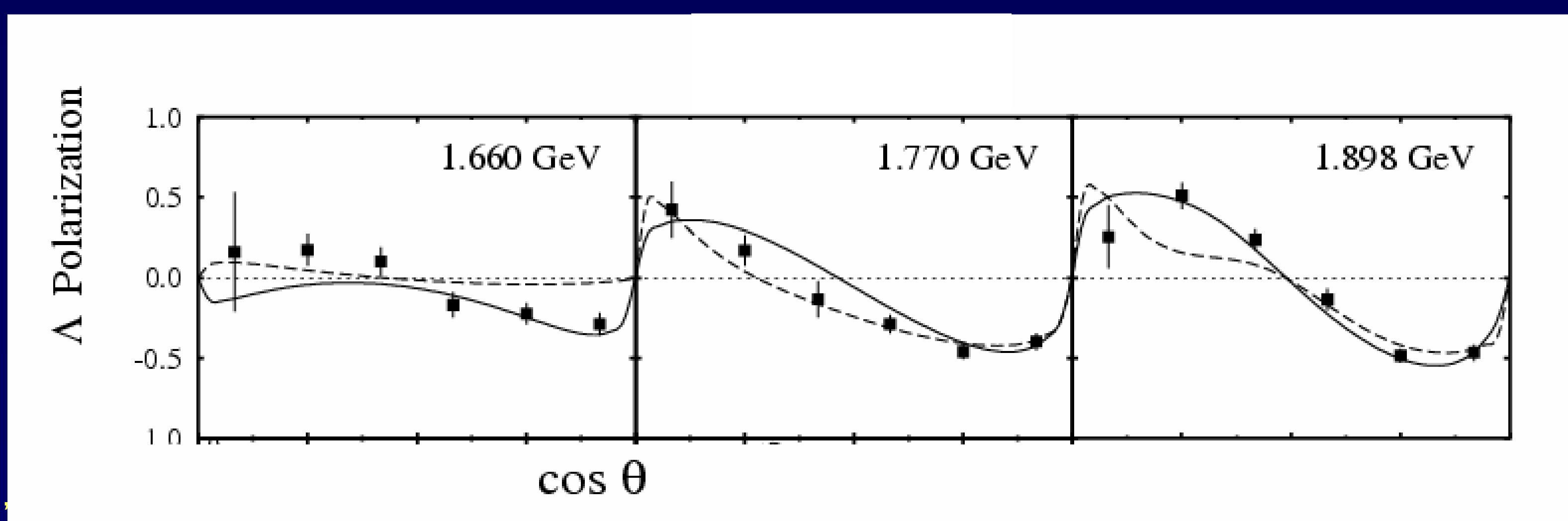
Cornelius Bennhold, George Washington University

Polarization observables for $\gamma N \rightarrow K\Lambda$

Polarized photons

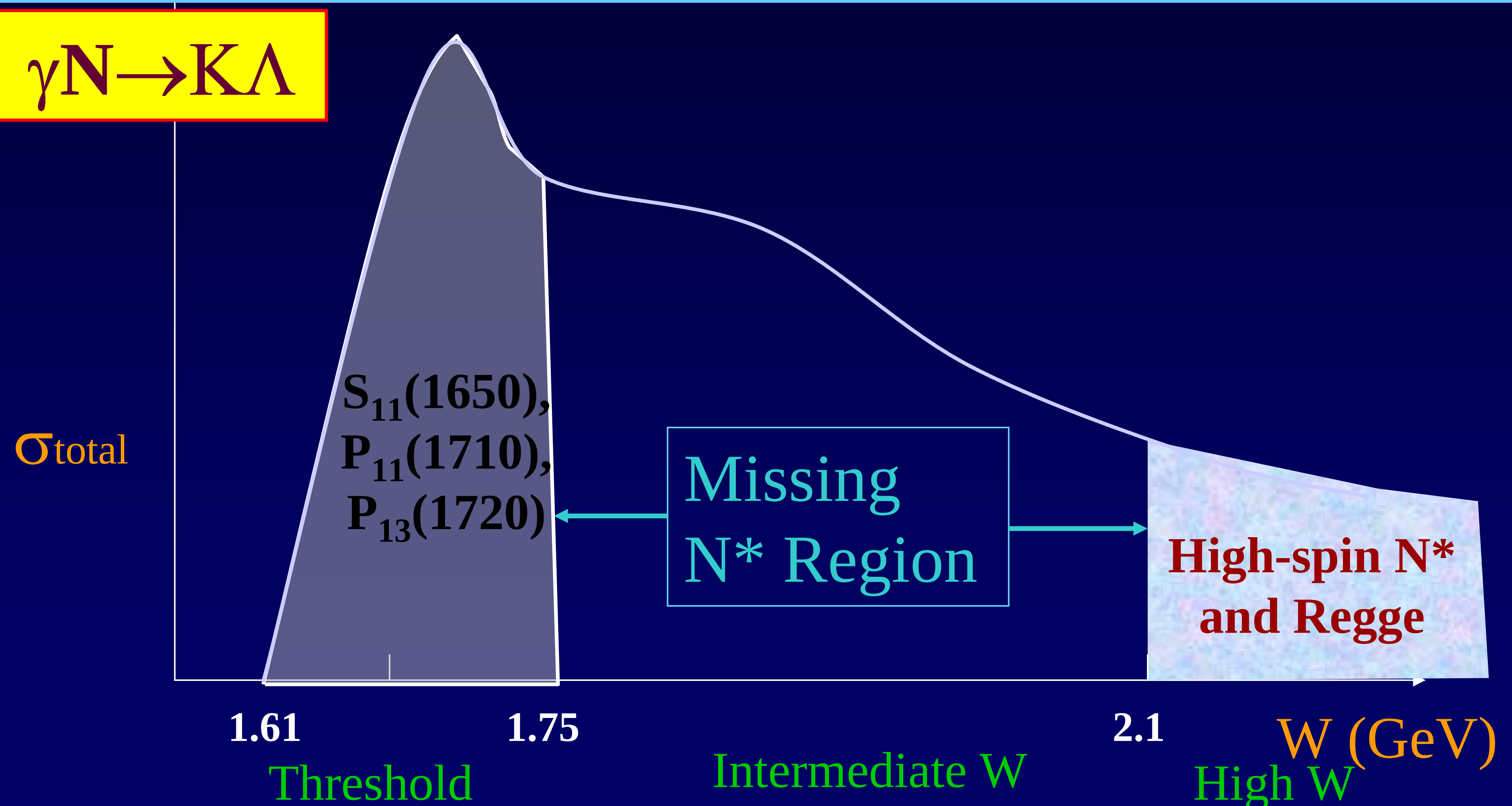


Λ Recoil



Divide energy region into three parts:

- **Threshold region (1.61 – 1.75 GeV):** $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$
- **Missing N* region (1.75 – 2.1 GeV):** D_{13} (1900),…
- **High-spin N* region (2.1 – 2.4 GeV):** $G_{17}(2190)$,…



Threshold Region

New Topic

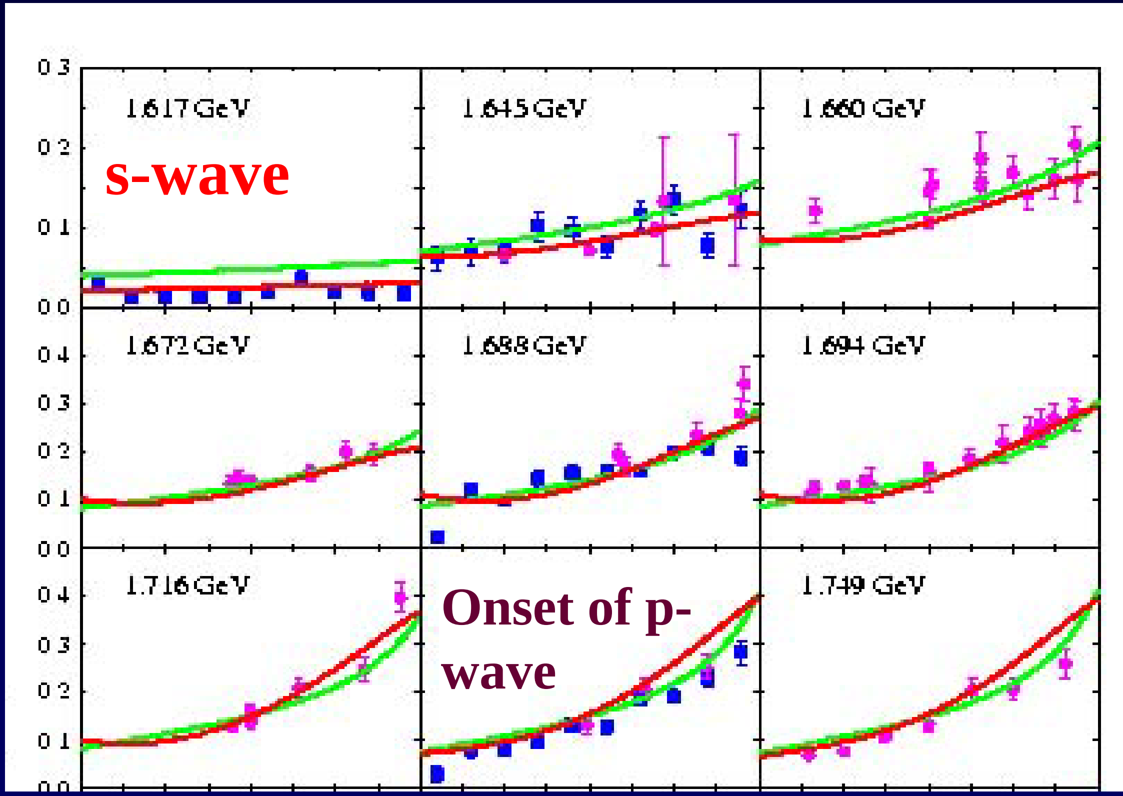
Threshold Region: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$

What does the quark model predict? (Capstick, Roberts)

N^*	$\Gamma_{K\Lambda}$	
$S_{11}(1650)$	large	√
$D_{15}(1675)$	zero	√
$F_{15}(1680)$	zero	√
$D_{13}(1700)$	small	√
$P_{11}(1710)$	large	√
$P_{13}(1720)$	large	√

Result of coupled-channels analysis for:

$\gamma p \rightarrow K^{+}\Lambda$ and $\pi^{-}p \rightarrow K^{0}\Lambda$



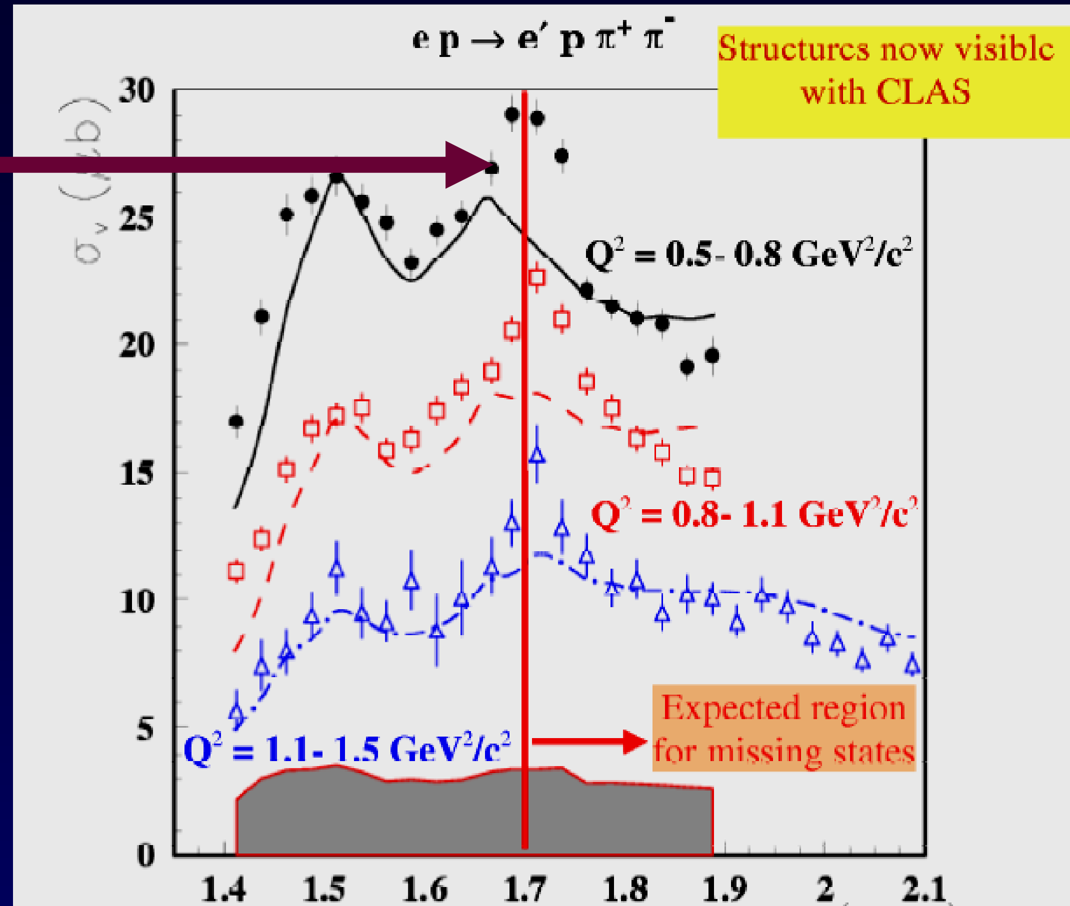
New result (prelim.):

$S_{11}(1650)$ 1610 – 1650 MeV

$P_{11}(1710)$ 1650 or 1730 MeV ⇒ possibly 2 different N*?

$P_{13}(1720)$ 1660 – 1720 ⇒ *but* total width is 40-70 MeV!

Another signal for a new P_{13} around 1700?

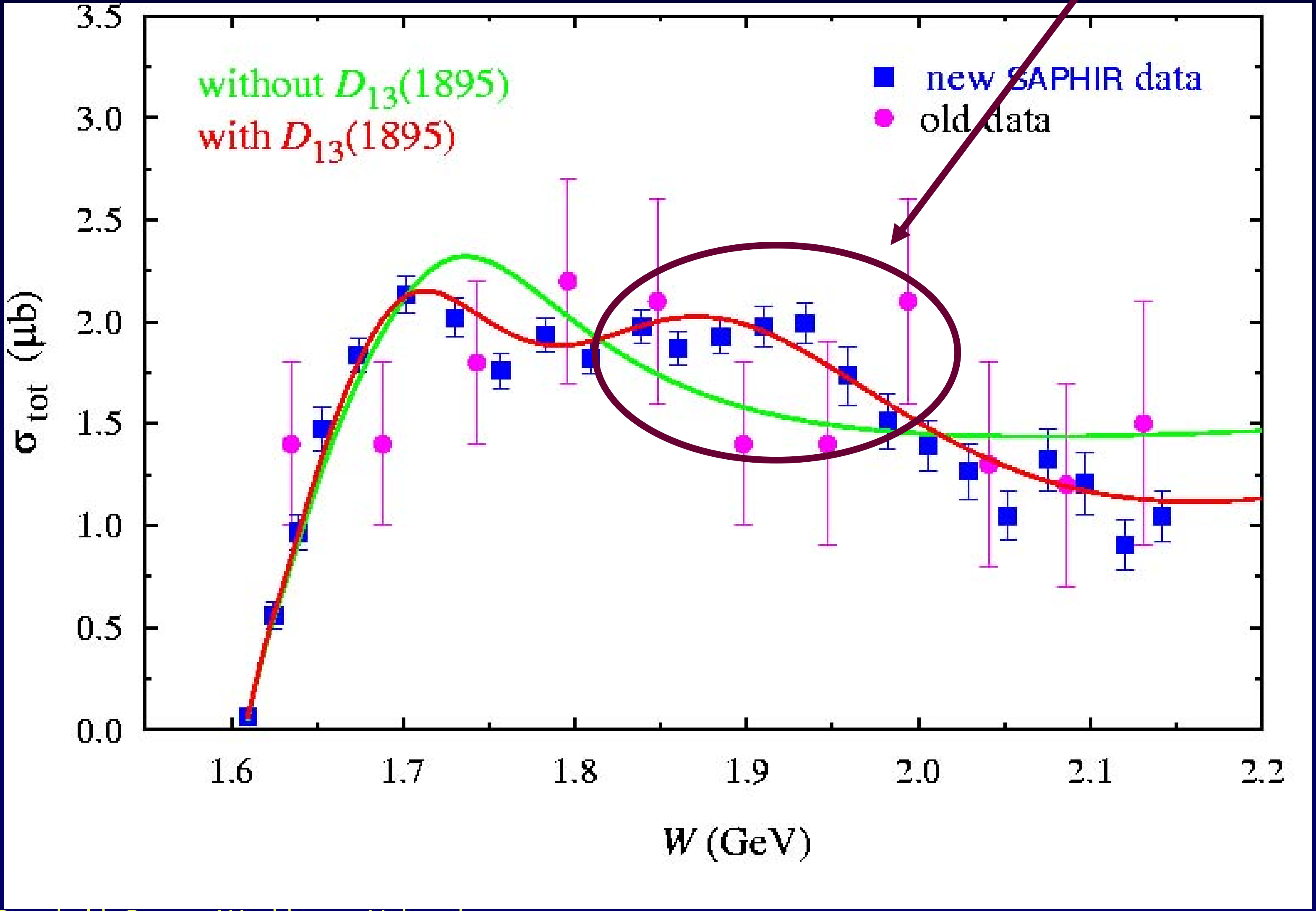


	Mass (MeV)	Γ (MeV)	B(Δπ) (%)	B(Nρ) (%)
our fit of PDG P_{13}	1725 ± 20	114 ± 19 ± 29	63 ± 12 ± 17	19 ± 9 ± 14
PDG values	1650−1750	100 − 200	absent	70 − 85
new P_{13}	1720 ± 20	88 ± 17 ± 25	41 ± 13 ± 20	17 ± 10 ± 17

Missing N* region

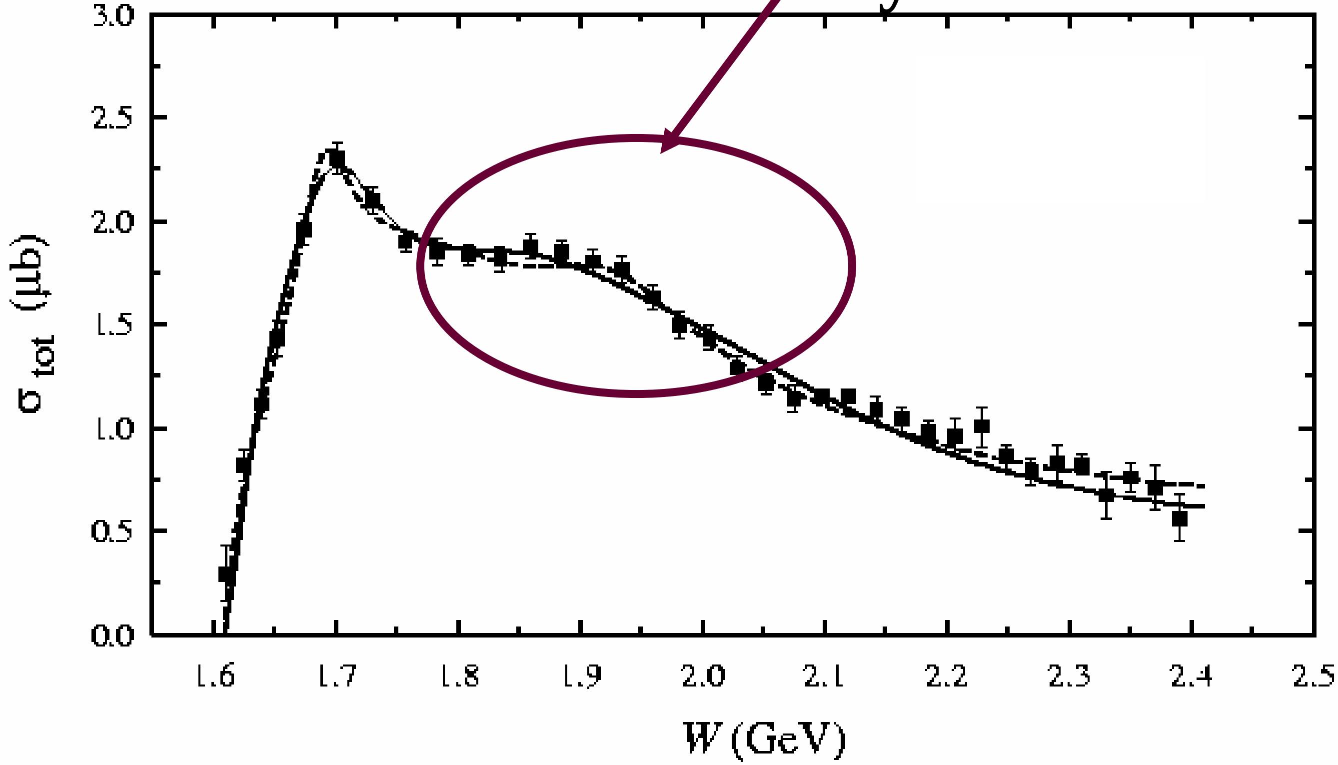
New Topic

Before 2003: suggestion for a new resonance, D_{13}(1900). No sign of any other states.



Bump around 1900 MeV is also in the new data, but less pronounced

SAPHIR data: ⇒ talk by K.H. Glanders



New resonances in $\gamma N \rightarrow K\Lambda$ **in the region 1.75 < W < 2.1 GeV** (preliminary)

N* State	Mass range (MeV)	Particle Data Group
P_{13}	1880 – 1930	P_{13} (1900)**?
D_{13}	1820 – 1880	D_{13} ---
D_{13}	2000 – 2080	D_{13} (2080)**?
D_{15}	1970 – 2030	D_{15} ---
F_{17}	1890 – 1950	F_{17} (1900)**?

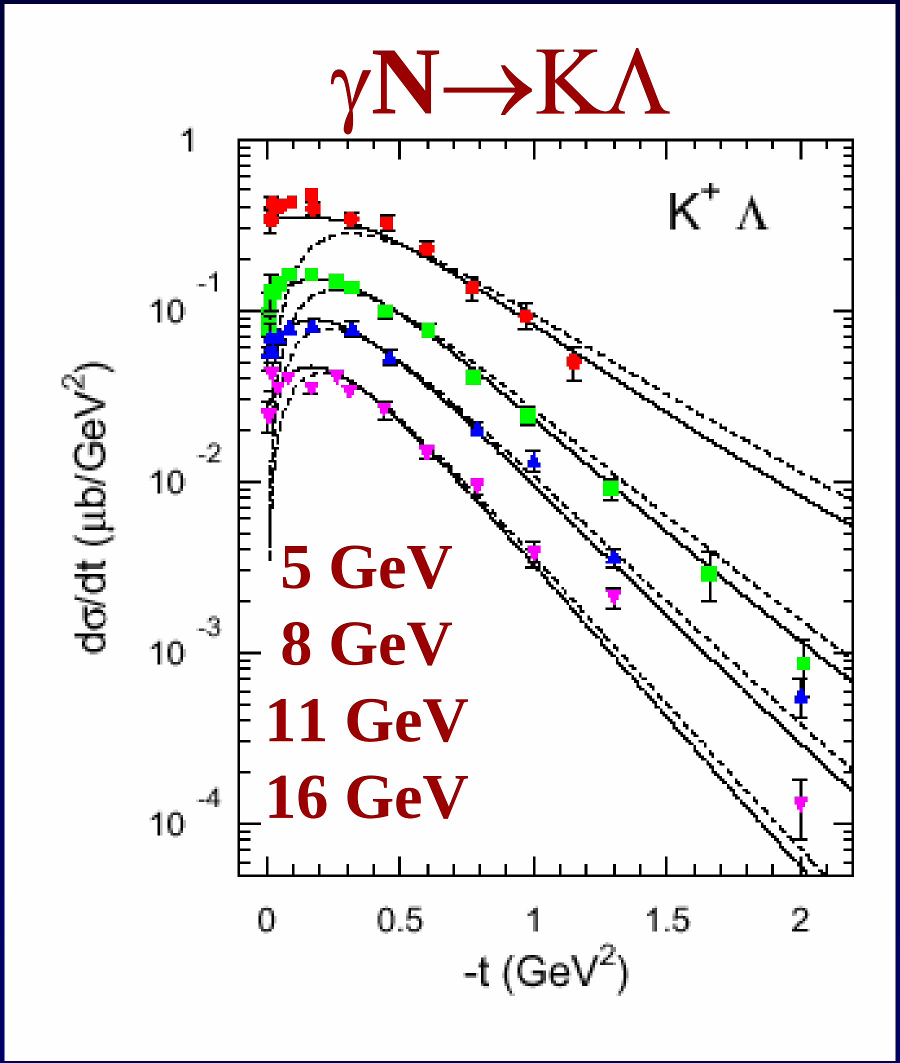
Comparison with C-R quark model in the region $1.75 < W < 2.1$ GeV

Quark model state	PDG	$\Gamma_{K\Lambda}$	our result
$[P_{13}]_2(1870\pm50)$	missing	small	-
$[P_{13}]_3(1910\pm50)$	$P_{13}(1900)$**	zero	-
$[P_{13}]_4(1950\pm100)$	missing	large	$P_{13}(1880\text{-}1930)$
$[P_{13}]_5(2030\pm100)$	missing	small	-
$[D_{13}]_3(1960\pm50)$	missing	***very large***	$D_{13}(1820\text{-}1880)$
$[D_{13}]_4(2055\pm100)$	missing	large	$D_{13}(2000\text{-}2080)$
$[D_{13}]_5(2095\pm100)$	$D_{13}(2080)$**	zero	-
$[D_{15}]_2(2080\pm50)$	missing	large	$D_{13}(1970\text{-}2030)$
$[D_{15}]_3(2095\pm50)$	missing	large	
$[F_{15}]_2(1980\pm50)$	missing	zero	-
$[F_{15}]_3(1995\pm50)$	$F_{15}(2000)$**	zero	-
$[F_{17}]_1(2000\pm50)$	$F_{17}(1900)$**	zero	$F_{17}(1890\text{-}1950)$

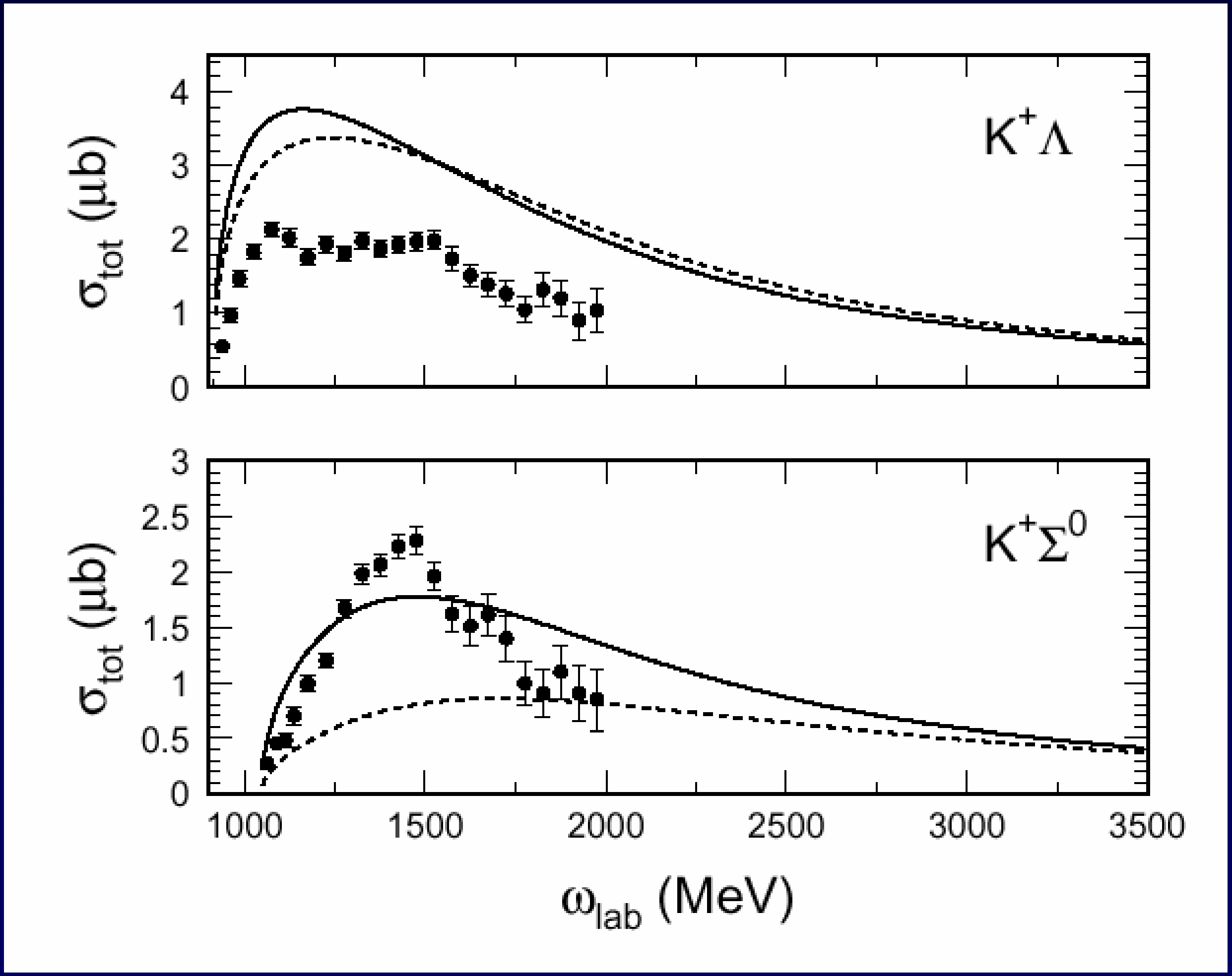
High energy (Regge) region

New Topic

At high W, but low t: *Regge trajectories*



How does Regge theory work in the N* region?



Magnitude okay within factor 2 but…
no structure!

How to transition from N* into Regge region??

Conclusions: New resonances in $\gamma N \to K\Lambda$ (preliminary)

- Four new resonances for $\gamma N \to K\Lambda$, in addition to $D_{13}(1900)$
- In comparison to Capstick-Roberts quark model:
  - Only one N* with "small" or "zero" couplings to $K\Lambda$ channel appears. Nine others do not appear.
  - All of the N* with "large" couplings to $K\Lambda$ channel appear.
  - The $D_{13}(1900)$ with a "very large" coupling has already been seen in previous SAPHIR data.

Are the missing N* finally appearing?

- Must follow up with:
  - Partial-wave analysis $\to$ need polarization observables!
  - Full coupled channels analysis (talk by A. Waluyo)